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Creep damage evaluation for HAZ of Mod. 9Cr-1Mo steels under multi-axial stress conditions

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Abstract

This study is concerned with the creep damage evaluation for fine grained heat affected zone (HAZ) of Mod. 9Cr-1Mo steel. Circumferentially notched bar creep rupture tests have been conducted in order to examine the effect of multiaxial stress state on creep rupture and creep damage of the fined grained HAZ. The simulated fine grained HAZ has been used. Finite element predictions based on a continuum damage mechanics model with ductility exhaustion approach has been used to predict the creep rupture and the creep damage in the notched specimens. It is found that a ductility exhaustion approach provides very large creep damage which leads to too conservative prediction of creep life for notched specimens.

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Keywords: Creep damage; Life prediction; High-choromium streel; Type VI fracture; Damage mechanics; Multiaxiality

1. Introduction

High-chromium ferritic heat resisting steels have been used for boiler components in ultra super critical (USC) thermal power plants operated at about 600°C, because of their excellent creep properties. However it is well known that creep strength of the welded joints of these steels is decreased during long-term use at higher temperatures due to Type-IV creep damages formed in the fine grained heat affected zone (HAZ). Fine grained HAZ are subjected to complex multiaxial stress conditions due to constraint effect on the deformation from the base and weld metals. It has been pointed out that the stress multiaxiality has an influence on creep damage evolution [1-2]. It is, therefore, needed to identify the

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effect of multiaxial stress condition on creep damage in fine grained HAZ and to be able to predict the creep rupture and the creep damage under multiaxial stress conditions for preventing the type IV fracture.

In this study, circumferentially notched bar creep rupture tests have been conducted using simulated fined grained HAZ specimens of 9Cr steels in order to examine the effect of multiaxial stress state on creep rupture and creep damage. Finite element predictions based on a continuum damage mechanics model with ductility exhaustion approach [3] has been applied to predict the creep rupture and the creep damage in notched specimens.

2. Creep tests

2.1. Material

The material used is modified 9Cr-1Mo steel (ASME Grade 91). The chemical composition of the steel is shown in Table 1. The material was supplied as a plate of 66 mm in thickness. This plate was normalised at 1055 ^{o}C for 90 minutes, cooled and then tempered at 780 ^{o}C for 90 minutes.

The heat treatment to simulate heat affected zone of Mod. 9Cr-iMo steel is shown in Fig. 1, after which, simulated post-weld heat treatment (PWHT) at 720 ^{o}C for 2 hours was applied. The heat treated material is hereafter referred to as simulated HAZ. Microstructure of the simulated HAZ is shown in Fig. 2. Average value of the hardness of the simulated HAZ is 202Hv.

2.2. Specimen

Circumferentially double notched bar specimens were used to study the effect of stress multiaxiality on creep rupture behavior. Geometries of the specimens are shown in Fig. 3, which are based on the code of practice for notched bar testing [4]. A diameter of notch throat d_{no} is 5.64 mm. Three different notch shapes A, B and C have been chosen to give the notch acuities d_{no}/R = 3.00, 9.89 and 29.7, respectively, where R is radius of notch root. Elastic stress concentration factors K_t for notch shapes A, B and C are 1.60, 2.36 and 3.59, respectively.

Table 1. Chemical composition of the modified 9Cr-1Mo steel (wt%)

C	Si	Mn	P	S	Cr	Ni	Mo	V	Nb
0.1	0.38	0.42	0.011	0.001	8.43	0.04	0.98	0.2	0.08

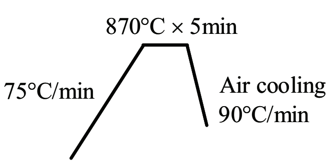

Fig. 1. Heat treatment condition for simulated fine grained HAZ

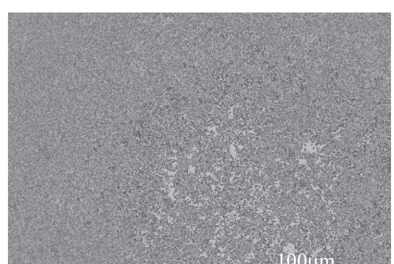

Fig. 2. Microstructure of the simulated HAZ.

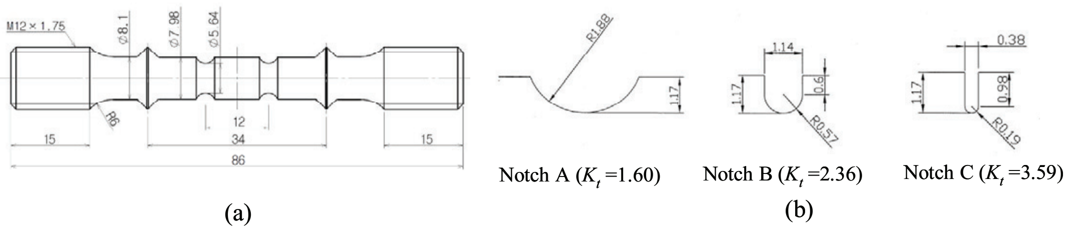

Fig. 3. Geometries of circumferentially double notched bar specimen: (a) whole specimen and (b) details of notch geometries

2.3. Test results

Creep tests have been conducted at 650 °C. Fig. 4 shows the rupture for the notch bar specimen. In Fig. 4 the open symbol shows the relationship between the rupture time and the net section stress of the specimen, whilst the solid symbol shows that between the rupture time and the reference stress. The net section stress is obtained from simply dividing testing load by initial cross-sectional area at the notch root, which can easily compared with the uniaxial creep test data. Notch strengthening is observed in Fig. 4 for all notches, and a trend with notch acuity can be found. Regarding the reference stress, the von-Mises equivalent stress at skeletal point [4] under creep steady state is used as the reference stress. It is clear in Fig. 4 that when the reference stress is used, the difference of the notch shapes can not be found and the rupture data is good agreement with uniaxial data.

The reduction of area at the ruptured notch is plotted against rupture time in Fig. 5. The reduction of area of the uniaxial specimen is also plotted for comparison. It is seen that the reduction of area in uniaxial specimen does not change with rupture time, whilst the creep ductility of the notched bar specimen decrease with rupture time and notch acuity. These results suggest that the effect of multiaxial stress state on creep ductility is significant for the tested material.

Fig. 6 shows the comparison of the experimental creep ductility with the analytical prediction models of creep ductility under multiaxial stress. In order to compare notch and uniaxial specimens, the reduction of area was adopted as a measure of the creep ductility under multiaxial and uniaxial stress condition. The stress triaxiality σ_m/σ_e at skeletal point under steady state is used as the parameter of multiaxiality, where σ_m and σ_e are hydrostatic and von Mises equivalent stress, respectively. In Fig. 6, the creep ductility under multiaxiality ε_f^* is normalised with that in uniaxial specimen, which is considered as constant and set such that ε_f =2.41 from Fig. 5. The creep ductility under multiaxial conditions is compared with the prediction of Rice and Tracy model (Eq. 1) [5], and Cocks and Ashby model (Eq. 2) [6].

$$\frac{\varepsilon_f^*}{\varepsilon_f} = \frac{0.521}{\sinh(3\sigma_m / 2\sigma_e)}, \tag{1}$$

$$\frac{\varepsilon_f^*}{\varepsilon_f} = \sinh\left[\frac{2}{3}\left(\frac{n-1/2}{n+1/2}\right)\right] \bigg/ \sinh\left[2\left(\frac{n-1/2}{n+1/2}\right)\frac{\sigma_m}{\sigma_e}\right], \tag{2}$$

where n is stress index for Norton law and is taken as 6.88 from uniaxial creep tests. It may be seen in Fig. 6 that both models give similar predictions and are in reasonable agreement with the experimental data.

To examine the effect of stress multiaxiality on creep damage, longitudinal cross-sections of notched bar specimens were observed with SEM to detect the creep void. Fig. 7 shows typical distributions of void area fraction across the throat of unbroken notch for the notched bar specimens with notch A and B. It is found from this figure that, although creep damage was observed at the root and the center of the

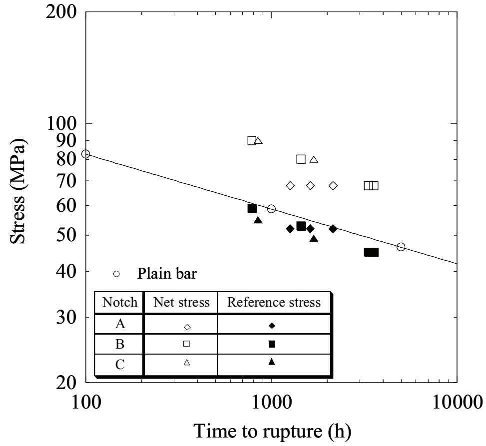

Fig. 4. Relation between stress and rupture time

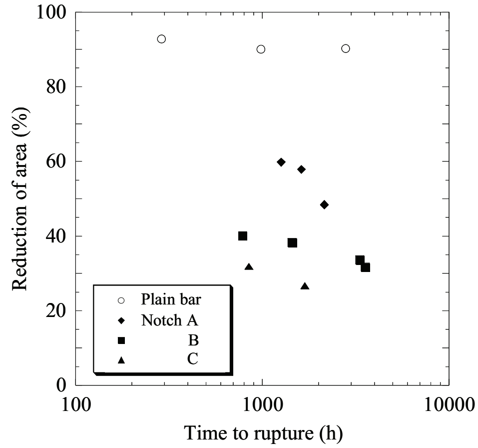

Fig. 5. Relation between rupture time and reduction of area

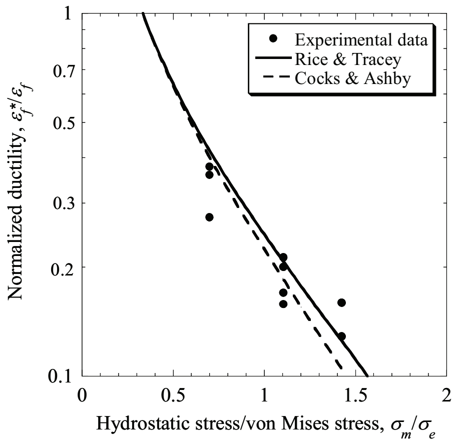

Fig. 6. Comparison of the experimental creep ductility with analytical multiaxial creep ductility model

notch for both specimens, the creep damage was concentrated towards the notch root with increasing notch acuity.

3. F.E. predictions of notched bar behaviour

3.1. Material model

To incorporate the effect of tertiary creep, a creep damage approach is used based on the continuum damage mechanics. Von Mises equivalent creep strain rate can be expressed as follows:

$$\dot{\varepsilon}^c = B\frac{\sigma_e^n}{(1-D)^q}, \tag{3}$$

where B, n and q are material constants. D is damage parameter and is established such that $0 \le D \le 1$ and failure occurs when $D = 1$. In this study D is defined as the ratio of the creep strain to the creep ductility and the rate of accumulation of damage is given as

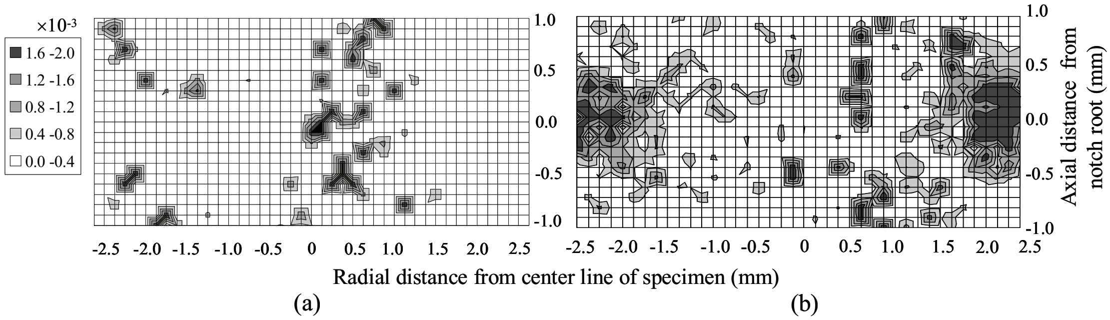

Fig. 7. Distributions of void area fraction across the throat of unbroken notch for specimen with (a) notch A (t_r = 2145h) and (b) notch B (t_r = 3560h)

$$\dot{D} = \frac{\dot{\varepsilon}^c}{\varepsilon_f^*} \tag{4}$$

where ε_f^* is the multiaxial creep ductility. To ensure that all stress components reduce to zero as $D \to 1$, damage is incorporated into the elastic term by allowing the Young's modulus E to reduce to zero as $D \to 1$, i.e.,

$$E = E_0 (1\text{-}D) \tag{5}$$

where E_0 is Young's modulus for an undamaged material.

3.2. Results and discussion

Finite element (FE) predictions of creep rupture and damage in the notched bar specimens of the simulated HAZ were conducted using the commercial code, ABAQUS 6.10 [7]. In this study, the effects of plastic strain and large geometry changes are not included. Due to the geometrical and mechanical symmetry, only half of the specimens was meshed with linear axisymmetric elements. Young's modulus E_0 and Poisson ratio are taken as 100,200 MPa and 0.3, respectively. Material constants for creep law in Eq. (3) are fitted to the experimental data for uniaxial specimen and are shown in Table 2. The effect of stress multiaxiality on creep ductility was taken into consideration using Cocks and Ashby model in Eq. (2).

The predicted rupture time, which is defined as a time when the valued of D in the first element across the notch reaches 1, is compared with experimental results in Fig. 8. It is founded that FE analysis provides more conservative prediction of rupture time with increasing notch acuity, i.e. stress multiaxiality. It means that Cocks and Ashby model overestimates the degradation of creep ductility in the case where stress multiaxiality is high.

Fig. 9 shows contours of creep damage at the notch throat. Creep damage is concentrated towards the notch root with increasing notch acuity. This result is in agreement with the experimental result except that creep damage was present at the center of the notch for notched specimens.

4. Conclusions

In this study, circumferentially notched bar creep rupture tests was conducted on simulated fined grained HAZ specimens of 9Cr steels. It is confirmed that multiaxial stress states have a significant effect on the creep rupture and damage. Finite element predictions based on ductility exhaustion approach was applied to predict the creep rupture and the creep damage in notched specimens. It is concluded that a ductility exhaustion approach provides very large creep damage which leads to too conservative prediction of creep life for notched specimens.

Table 2 Material constants for the simulated HAZ of mod.9Cr-1Mo stress at 650ºC (for B and n, stress is in MPa and time in hours)

B	n	q	ε_f
6.70×10^{-17}	6.88	2.40	0.310

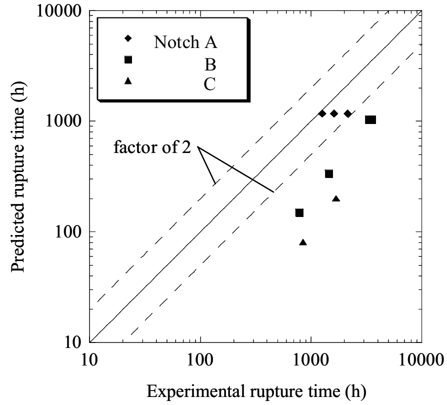

Fig. 8. Comparison of experimental and predicted rupture times

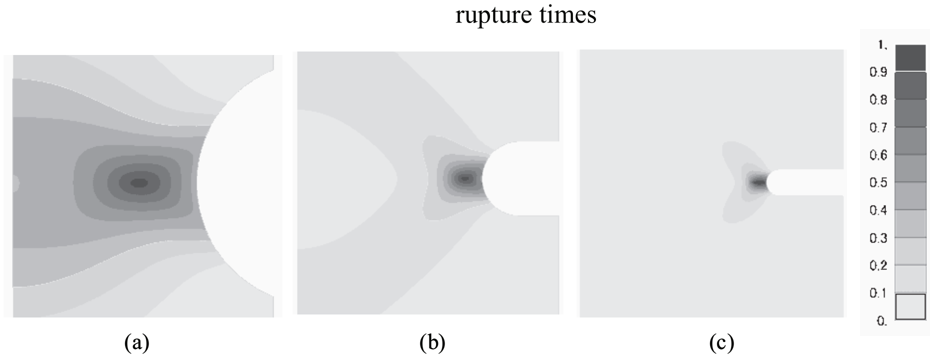

Fig. 9 Contour plot of damage at notch throat of notch (a) A, (b) B and (c) C

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